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LATE CENOZOIC CHRONOLOGY OF THE UPPER VERDE VALLEY, ARIZONA[1]

RICHARD H. MAHARD[2]

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ABSTRACT

The Upper Verde Valley of Central Arizona lies between the Mogollon Rim of the Colorado Plateau and the Black Hills Range, a fault-block mountain. The valley was once the site of a lake created by a lava-tuff dam across the Verde River.

Relationships between lake sediments, Paleozoic sediments, a lava sequence, faults, stream gravels, and pediments, reveal details of Cenozoic history of Upper Verde Valley which are of significance in interpreting broad regional events. In late Miocene time, before Upper Verde Valley existed, gravels were deposited on what is now the high Plateau surface. Headward growth of Verde River resulted in capture of north and east flowing drainage and excavation of the first Upper Verde Valley. In this valley was deposited a great thickness of gravel, locally derived in part, but also containing pre-Cambrian rock types.

[1] Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Faculty of Pure Science, Columbia University. June 1949.

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Pediments developed on the plateau side of the valley at this time. Re-excavation then occurred. Outpouring of lava created a dam which blocked the river. Deposition of sediments in Verde Lake was contemporaneous with part of the igneous activity. These and other relationships indicate a Pleistocene rather than Pliocene date for Verde Lake sediments. Lava flows of the Black Hills Range associated with lake sediments are cut by the main movement along the Verde Fault which bounds the Black Hills.

Excavation of the lake sediments is now occurring and has resulted in the formation of pediments and terraces in the valley.

INTRODUCTION AND ACKNOWLEDGMENTS

The broad objective of this study is to add to knowledge of events of Late Cenozoic history of the Colorado Plateau province. In detail the study concerns itself with the chronology of Upper Verde Valley, which contains an unusual series of Late Cenozoic lake beds and lavas. This allows deciphering of diastrophic and erosional events in a way not possible in the adjoining Grand Canyon district of the Colorado Plateau Province where Late Cenozoic history is largely erosional and sedimentary deposits lacking.

The only paper which deals specifically with details of the Upper Verde Valley is that of Jenkins (1923). Reber (1921) and Lindgren (1926) studied the Black Hills Range and Robinson (1913) the lavas of the nearby Colorado Plateau.

This paper was prepared under the supervision of Professor A. N. Strahler of Columbia University. The writer expresses appreciation to him for counsel, and critical and helpful reading of the manuscript. Professor E. D. McKee of the University of Arizona and the Museum of Northern Arizona gave valuable advice and visited the field localities. Dr. H. S. Colton kindly made available the excellent facilities of the Museum of Northern Arizona which materially aided the progress of field work. To Dr. C. A. Anderson of the U. S. Geological Survey the writer is indebted for many courtesies and helpful suggestions. William A. Eames gave valuable field assistance during the summer of 1947.

For typing the manuscript and for aid in countless ways, the writer is grateful to his wife, Marian Neir Mahard.

PHYSICAL GEOGRAPHY

Location of the Area

The Upper Verde Valley lies almost in the center of Arizona (Fig. 1). The valley is about midway between Flagstaff to the north and Prescott to the west. Important towns in the valley are Clarkdale and Cottonwood which dominate the northwest or upper part of the region, and Camp Verde serving the southeast or lower end (Fig. 2). Highway U.S. 89A enters the valley from the north via Oak Creek Canyon, passes through Cottonwood, Clarkdale, and Jerome, then crosses the Black Hills Range.

The location of Upper Verde Valley between the Mogollon Rim and Black Hills Range is a matter of primary geologic importance. The boundary between the Colorado Plateau province and Basin-Range province is generally drawn

along the valley. Topographically there is adequate reason for so doing; but structurally and stratigraphically this boundary is not well founded.

Elevation and Climate

The Verde River enters Upper Verde Valley at the north at 3600 feet elevation and leaves the valley at elevation 3000 feet. Within the valley there is a relief o

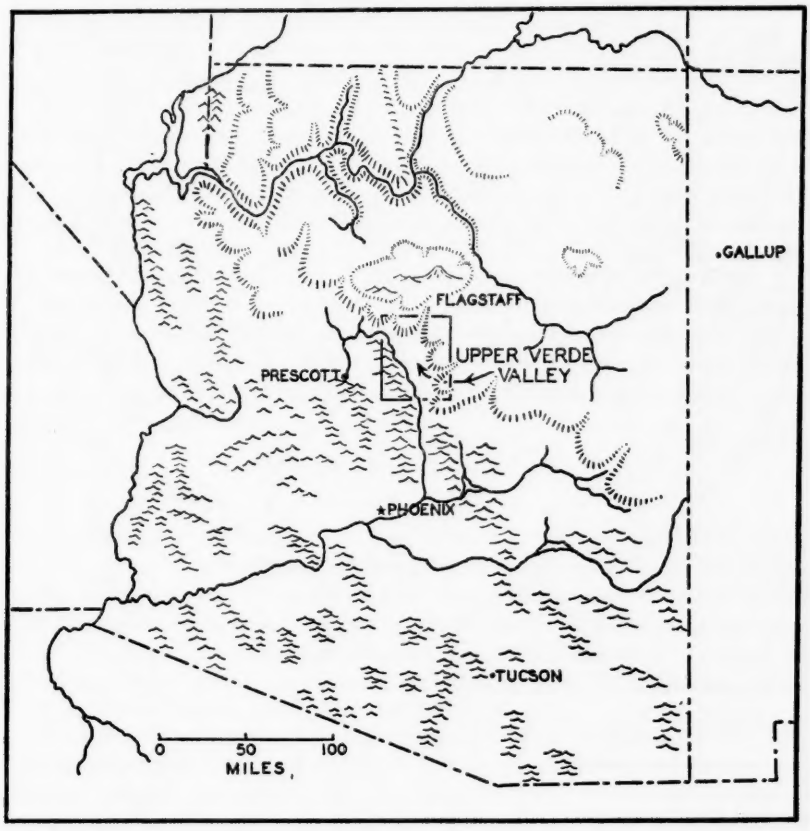


FIG. 1

approximately 1000 feet. The range of elevation of 3500–4000 feet is typical for the valley as a whole.

The edge of the Mogollon Rim is at elevation 5500 to 7000 feet and the Black Hills Range is 6000 to 6500 feet, rising to 7500 feet in Mingus and Woodchute Mountains.

The Upper Verde Valley has hot summers and mild winters and scanty rainfall. Summer daytime temperatures frequently exceed 100° and the low elevation

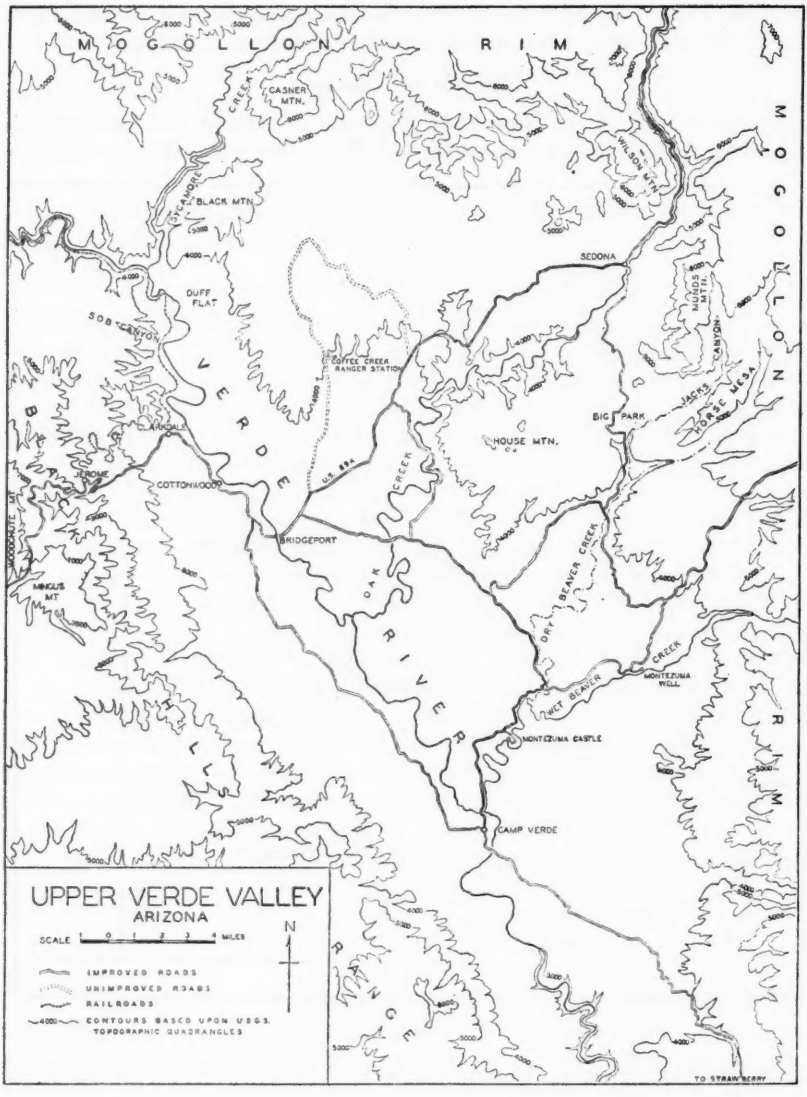


FIG. 2

hinders the cooling off at night which is characteristic of areas above 5000 feet. Rainfall is not uniformly distributed throughout the year; there are two peak seasons, the most important being the mid-summer period of relative cloudiness at which time violent thunderstorms may occur. Approximately 45% of the

yearly rainfall of 12 inches comes during the months of July, August and September, and 35% in the months of December, January, and February.

Erosion and Drainage

Within the valley erosion by running water is dominant. Stream courses which are dry most of the time are ordinarily partly choked with poorly sorted alluvium being sporadically moved down stream at times of flood.

The Verde River flows from north-northwest to south-southeast through the valley. The chief perennial tributary of the Verde within the limits of the Upper Valley is Oak Creek which has its origin in extensive springs along its canyon cut into the edge of the Mogollon Rim. At the northern end of the valley Sycamore Creek, another spring-fed stream from the plateau, flows into the Verde; and at the south end of the valley, near Camp Verde, Wet Beaver Creek, also perennial, enters from the east. Within Upper Verde Valley not a single perennial stream enters the Verde from the Black Hills Range, although that range is sufficiently high and well-watered to support a pine forest along its crest.

The Verde River is one of the most reliable streams in Arizona and within Upper Verde Valley the water is extensively utilized for irrigation. Well-watered fields of alfalfa, fruit trees, and garden crops extending for several hundred yards on both sides of the river contrast vividly with the desert flora of bunch grass, mesquite, and cactus.

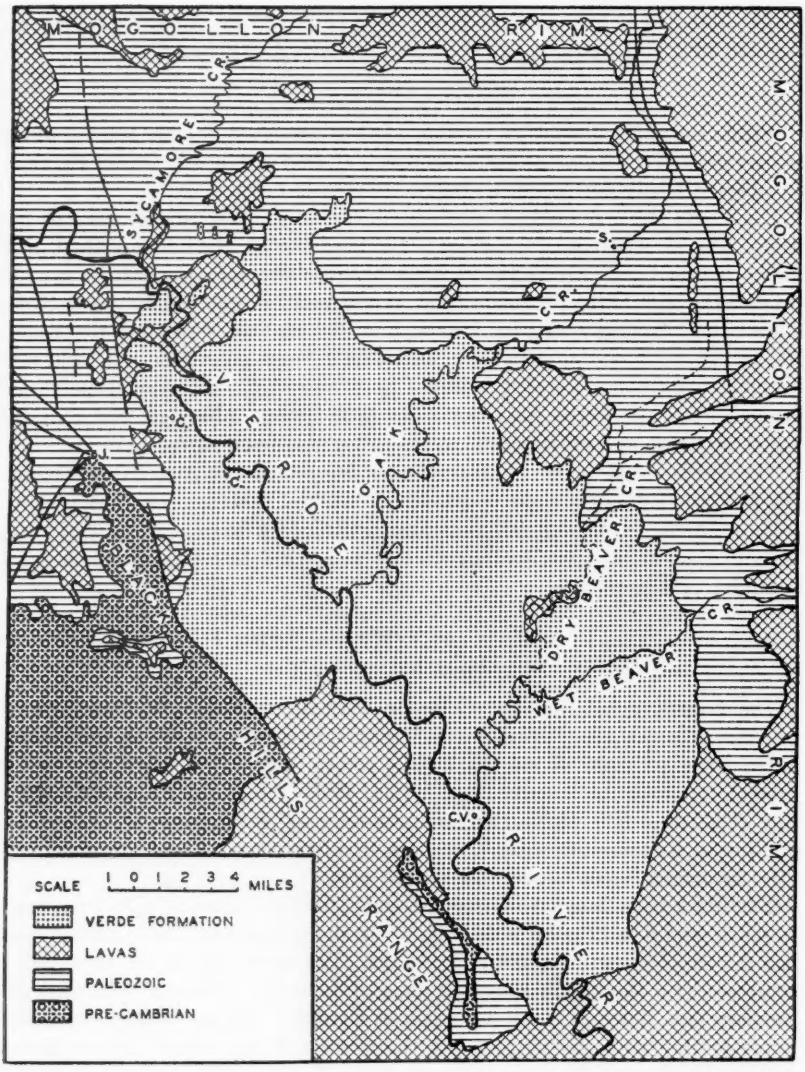
GEOLOGY OF BOUNDARY AREAS

Black Hills Range

The boundary between the Colorado Plateau province and Basin Range province is drawn along Upper Verde Valley, thus placing the Black Hills Range in the latter province. If the Black Hills Range was located in central Nevada it would no doubt be described as a typical Basin Range block mountain structure. The range falls within the "mountain region" in Ransome's (1903, p. 14) division of Arizona into three northwest trending zones: "the plateau region", "the mountain region", and "the desert region".

The Black Hills Range is an irregular, elongated block some 20 miles long, north to south, and 8 to 12 miles wide (Fig. 3). In the middle part the mountain mass has the simplest outlines and cross section. The north end of the mountain is composed of a thoroughly dissected mass of disturbed Paleozoic sediments and Tertiary lava flows. A few miles north of Clarkdale the mountain area merges imperceptibly with the Plateau. At the south end the rugged terrain merges without break with the irregular mass of the Bradshaw Mountains.

In the north central part, the Black Hills Range is a horst capped by northward dipping Paleozoic sediments which are in turn overlain by Tertiary volcanics. Mingus and Woodchute Mountains in the Jerome area owe their superior elevation to capping rocks. The mountain core in the central part is composed of pre-Cambrian rocks of many types, ranging from a complex of "greenstones" of volcanic origin to diorite, rhyolite porphyry, and granite (Lindgren 1926). In the pre-Cambrian rocks at Jerome were discovered massive sulphide copper


MOGOLLON RIM
SYCAMORE CR.
CLEAR CR.
DEER CR.
OAK CR.
BEAVER CR.
DRY BEAVER
WET BEAVER
CR.
CR.
CR.

placement along numerous parallel faults here reaches a maximum of 4000 feet. This figure was obtained by comparing the elevation of the Tapeats sandstone beneath the plateau with its elevation around Jerome. Most important of the faults is the Main or Verde fault which can be easily traced through the town site of Jerome. Displacement along this fault is 1700 feet at the United Verde Mine. The fault breaks Tertiary volcanics and is therefore more recent than these lavas. Additional discussion of the relationships of this fault is found in the section on chronology.

On the west side of the Black Hills Range, faults are undoubedly present but are more obscure. Geologic mapping currently being carried on by the U. S. G. S. (Anderson, C. A., 1947) reveals a striking pre-Cambrian fault parallel to the west side of the range. This suggests that recent faulting has occurred along lines of weakness established in very ancient geologic time.

Mogollon Rim

Overlooking Verde Valley from the northeast is the Mogollon Rim of the Colorado Plateau. In this region the rim is frequently called the Verde Breaks. The plateau edge is deeply trenched by youthful streams of which Oak Creek and Sycamore Creek are excellent examples. Dissection has resulted in the formation of buttes and mesas isolated from the plateau mass; examples are Wilson Mountain, Black Mountain, and Casner Mountain (Fig. 2).

Rocks exposed along the plateau edge are those of the upper part of the classic Grand Canyon section. Stratigraphically highest is the Permian Kaibab limestone underlain by the Toroweap sandstone. Below lies the cross-bedded Coconino sandstone, underlain by thick Supai red beds. The Supai consistently makes the foot hills of the escarpment, and more recent rocks of Upper Verde Valley frequently lie unconformably upon this formation. At the mouth of Sycamore Canyon and also in the "caps" atop the Black Hills Range, additional members of the Paleozoic section are exposed; these include Pennsylvanian Naco limestone, Mississippian Redwall limestone, Devonian Martin limestone, and Cambrian Tapeats sandstone.

The plateau in the region here under consideration is capped by Cenozoic lavas discussed in greater detail below.

The Mogollon Rim is by no means structureless. Minor folds are apparent in the areas of Supai outcrop, and Oak Creek Canyon is the site of faults of considerable magnitude currently being investigated by Mears (1948). Another fault similar to Oak Creek fault is found in Sycamore Canyon and has been studied by Price (1948). Additional detailed study of the Rim will doubtless reveal structures not now recorded.

GEOLOGY OF UPPER VERDE VALLEY

Verde Formation

The most conspicuous outcrops of rock within Upper Verde Valley are those of the Verde formation. This name is applied to a series of lake deposits which were originally described by O. P. Jenkins (1923, p. 69):

"The Verde formation consists of white limestones, gravels, sands, clay, and saline materials . . . The greater portion of the Verde formation is a hard impure, reprecipitated, cavernous limestone interbedded with sands, gravels, and clays . . . Near the border, or old shoreline, of the old Verde lake, conglomerate beds are in evidence. . ."

Jenkins' (1923) original hypothesis regarding the origin of Lake Verde required blocking of the Verde River by a basalt and pyroclastic dam 7 to 15 miles south of Camp Verde. No detailed study of the dam was attempted by the writer, but a reconnaissance of the area reveals a series of flows and tuff deposits, now deeply trenched by the Verde River, which are judged to be more than adequate to effectively impound the river waters.

The area of Lake Verde at its maximum extent, based upon present distribution of lake beds, was approximately 300 square miles. The maximum length was 40 miles and the maximum width 15 miles.

During the summer of 1947 the writer measured two sections of rocks of the Verde formation. As far as is known these are the first sections to have been measured and the first attempt to make a study of sediments composing the formation.

The two sections are shown in Fig. 4. The Clarkdale section was measured from a point along the west bank of Verde River one mile north of Clarkdale smelter, and the section ended atop the mesa which can be seen from the highway as one approaches Clarkdale. The Clarkdale section includes 733 feet of sediments which are exposed from elevation 3400 feet to 4133 feet above sea level at the place where the section was run. It is apparent from Figure 4 that the lower half of the section is composed of an alternating series of sandstones, siltstones, and limestones. At the halfway point the detrital material becomes finer and less abundant and the section ends in a series of thin bedded limestones.

The Bridgeport section was measured starting from a point along the Verde River two miles north of Bridgeport (U. S. 89A crossing of the Verde) and ending atop the sprawling mesas west of the Coffee Creek Ranger Station road. The total thickness of strata here measured was 1040 feet outcropping from elevation 3280 feet to 4320 feet. Sandstones and siltstones here constitute 75% of all strata measured, but in this section also the uppermost beds are largely limestone.

The two sections were measured at points five miles apart; since the beds are horizontal it may be assumed that any correlation between units would be apparent when the sections are arranged as in Fig. 4. It is clear that no correlation exists. The Verde formation is not composed of beds of material which were spread uniformly over wide areas but instead is built up of thin lenses of material of varying composition, the lenses overlapping and interfingering with one another.

The maximum thickness of Verde formation cannot be measured. To 1040 feet measured in the second section described above must be added an unknown thickness lying below the present river level. Jenkins (1923) records two well logs. One at the smelter at Clarkdale adds 690 feet to the beds exposed above the top of the well for a total of at least 1400 feet. The other well, near Camp Verde, is thought to have penetrated 1650 feet of Verde formation. This added to the exposures above the top of the well, makes a total of at least 2000 feet.

The writer, however, seriously questions the reliability of well logs in this region. Drillers obtaining well cuttings from the sandy lake beds could differentiate them

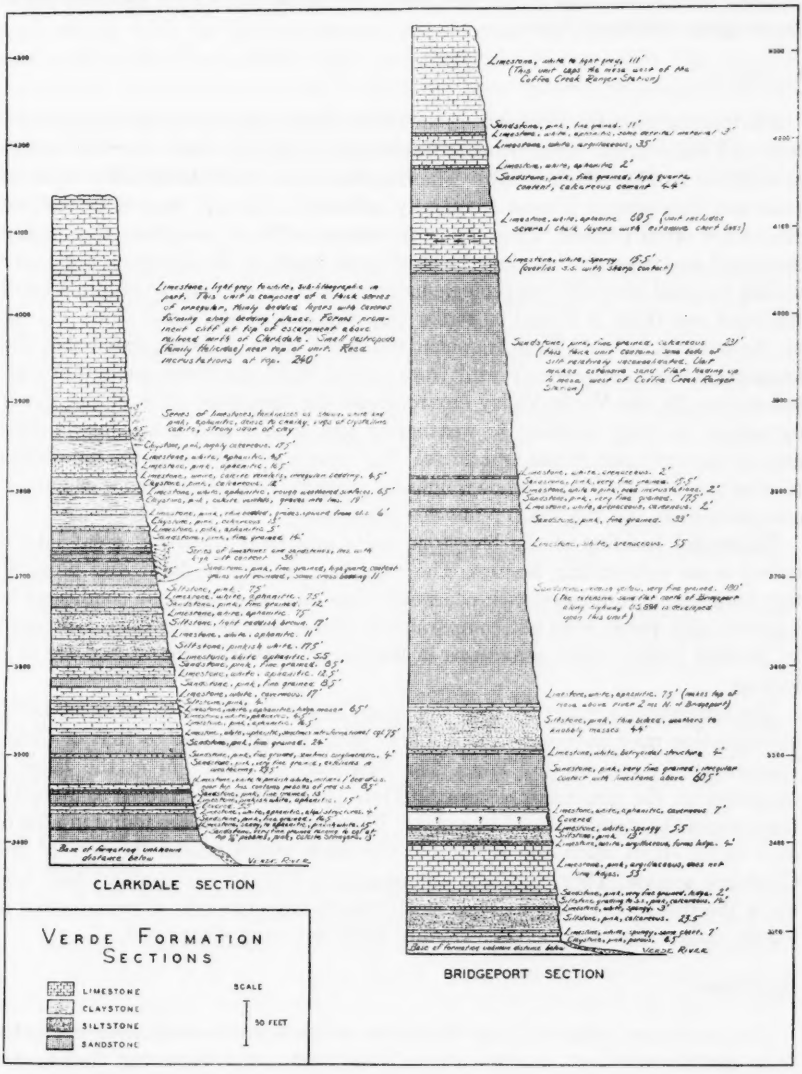


FIG. 4

from cuttings obtained from the underlying Paleozoic sediments only with great difficulty. Unfortunately, diagnostic fossils are absent.

The only reliable total thickness figure at present is obtained by subtracting

the lowest elevation of outcrop of the lake beds from the highest outcrop. At the south end of the basin the Verde River leaves lake beds at elevation 2900 feet; the highest outcrops are at 4300 feet. This thickness of 1400 feet represents the smallest maximum figure.

Limestones

The limestones in the two sections are undoubtedly the most striking lithologic type and their origin constitutes an interesting problem which warrants study in addition to that which follows. The limestones are characteristically white in color and their texture is most frequently aphanitic although vugs of crystalline calcite are often present. These beds are almost without exception thoroughly indurated and must not be thought of as weak marls or chalks which are easily broken to small bits with the geologic hammer; on the contrary, to obtain a hand specimen one often is forced to strike very vigorously and small chips will fly off the outcrop before a large fragment will break loose. It is suggested that the hardness of the limestone may result from reprecipitation and consequent thorough induration. In the Verde Valley environment the limestone units of the Verde formation are very resistent to weathering and erosion and hence form ledges and act as caps upon mesas and buttes. The weathered surface of the limestones is often characterized by extreme roughness resulting from the presence of numerous concavities and the sharp pinnacles between.

Horizontal bedding of the limestone units and their relatively great lateral extent is an outstanding feature. The complete absence of dome and pinnacle tufa forms or tufa masses with concentric banding indicates that conditions in ancient Lake Verde were not comparable to those described for Lake Lahontan by Russell (1885). Algal structures in the Verde formation limestones are also lacking.

The limestones apparently were deposited in a series of playa lakes as marls. Precipitation may have been the result of plant action similar to that of Chara (stonewort) in present day lakes. The existence of plant life in the lakes is indicated by the structures pictured in Plate 1 which are interpreted as incrustations about the stem of a reed-like plant. These incrustations are found in abundance lying about upon the surface of the mesa which marks the top of the Clarkdale section. They were also abundant in a limestone unit about half way up in the Bridgeport section. The limestones are unfortunately almost barren of fossils, only a few gastropods of family Helicidae were discovered.

Sandstones

The sandstones, siltstones, and claystones of the Verde formation are cemented with calcium carbonate and are generally well-indurated. However, they do not withstand weathering and erosion as well as the ledge-making limestones, and form the gentler slopes of the topography. Cross-bedding in the sandstones is strikingly rare which indicates that current activity during deposition was at a minimum.

Salines

Salt beds are not abundant in the Verde formation. In the vicinity of Camp Verde, however, there was operated until a few years ago a salt mine. At this place, mixed with the lake sediments, are deposits of thenardite along with smaller quantities of mirabilite, halite, and glauberite (Blake, 1890). This deposit undoubtedly was laid down when Verde Lake or an isolated playa upon the extensive lacustrine plain evaporated until only a rich brine remained from which precipitation occurred. The deposition of the salt indicates an arid climate and fortifies the hypothesis that Verde Lake basin was at times occuped by numerous separate playas.

Basal Breccia

There is abundant evidence that rising waters of ancient Lake Verde inundated an area of considerable relief. Previous to the emplacement of the lava and tuff dam, the Verde River and its tributaries were dissecting a region underlain by Paleozoic sediments and Tertiary lavas which were spread out from the plateau and the Black Hills margin and from vents within the valley itself. On to this landscape were deposited sediments of the Verde formation. The complexity of outcrop patterns of lake beds as seen today, therefore, is not only the result of accidents of erosion in the present cycle but also depends upon pre-lake erosion. Since the Tertiary lavas also poured out over an irregular surface developed on older rocks, an additional complexity is added. Thus in Upper Verde Valley today an observer may see being exhumed by present erosion both a pre-lava topography and a pre-Verde Lake topography.

One result of inundation by the lake and the blanketing of topography by lake sediments has been the development of an unusual basal breccia (Plate 2). This breccia is most conspicuous where the Verde formation lies upon lavas. Here fragments of lava, varying in size from a fraction of an inch to three feet in diameter and angular in outline, are embedded in a matrix of limestone or sandstone. The contrast in color between lava fragments and matrix adds to the unusual appearance of the breccia. Where lake beds overlie Supai formation, the basal breccia is also present but is not so conspicuous, partly because the color contrast is lacking and partly because the Supai surface was not strewn with as much residual rubble.

Study of the breccia suggests that the landscape inundated by lake waters was strewn with rubble. The unusual thickness of the breccia, as great as 20 feet in some localities, suggests that the rubble was loose enough to allow penetration of lake sediments to a considerable depth. Quite possibly when steep-sided, mantle-covered spurs were drowned, mud of the lake lubricated the mantle and sliding occurred which accounts for local thickening of the breccia.

Angular fragments of lava embedded in the breccia are frequently deeply weathered, some so thoroughly that they can be picked apart with bare hands; others show a band of weathering up to two inches in thickness. If the breccia represents a buried mantle as postulated above, it appears that boulders strewn around on the pre-Verde Lake landscape were subject to weathering under

climatic conditions different from those which prevail in the valley today. A more humid climate resulting in a greater rate of chemical decomposition is indicated.

Igneous Rocks

Extrusive igneous rocks of Upper Verde Valley are associated with the extensive San Francisco and Mormon Mountain volcanic fields and with extrusive igneous rock areas of the Black Hills Range and adjacent regions. The most detailed study of lavas of the plateau region north of the valley is that of Robinson (1913) which summarized earlier work of numerous men and serves as the basic study. More recently Colton (1937) has studied the San Francisco Mountain field and has divided igneous activity into five stages.

The most prominent areas of lava within the Verde Valley are those of House Mountain located 7 miles southwest of Sedona. Along highway 89A for several miles southwest of Sedona are isolated patches of lava overlying Supai formation and underlying beds of Verde formation. Duff Flat, 2 miles north of Clarkdale, is underlain by lava and the Verde River has trenched these flows to produce a spectacular steep-walled gorge, which may be viewed from the Clarkdale-Drake branch of the Santa Fe Railroad. North of the Clarkdale-Jerome highway, lavas are seen as isolated dark-colored hills which contrast strikingly with dominantly white lake beds.

At a point 8 miles north of Camp Verde, where Montezuma Castle highway follows the valley of Dry Beaver Creek, a significant lava locality was observed. At this point two thin lava flows are interbedded with members of the Verde formation. The lower interbedded flow has a total thickness of 23 feet and is composed of three distinct zones—a bottom zone of gray-green, earthy, material representing disintegrated lava, a middle zone of columnar-jointed material very little altered by weathering compared to the lower zone, and a top zone of amygdaloidal lava with the amygdules largely filled with crystalline calcite. It is possible that this lava zone may represent three distinct outpourings of lava. An interesting feature of the lower flow is the presence of channels cut in the lava surface by erosion of the flow; the channels are now filled with the characteristic basal, lake bed breccia.

One hundred feet of lake beds separate the multiple flow described above from the upper lava layer. The upper flow is 34 feet thick at the type locality along Dry Beaver Creek and does not show zoning characteristic of the lower. Nowhere were channels observed in its surface; it is, however, overlain by the breccia.

The two interbedded flows may be traced up the valley of Dry Beaver Creek for three miles. Both ascend northward and it seems likely that their source was in the House Mountain area.

CHRONOLOGY

Episode One

Plateau Gravel Deposition

Gravels containing quantities of pre-Cambrian pebbles have been discovered upon the surface of the Colorado Plateau at various localities from Fort Apache

Indian Reservation in east central Arizona northwestward to the west end of Grand Canyon. Koons (1948) published a short paper dealing wth gravels in the Hualpai Indian Reservation and proposed the name Frazier Well gravel. Price (1948) has discussed gravels, similar if not identical to those of Koons, in Sycamore Canyon region southwest of Flagstaff. Strahler (1949) reports finding gravels at the northern end of the East Kaibab monocline in Utah.

Gravels described by Price are of particular significance because of proximity of the deposit to Upper Verde Valley. Anderson, on Price's request, examined pebbles collected from the deposit and identified them as representing rock types found in Black Hills Range. Gravels were found at elevations greater than 6000 feet and it is obvious that they could not have been transported from Black Hills Range at any time after cutting of the present Upper Verde Valley which lies between the source rock areas and the gravel deposit at an elevation of less than 4000 feet.

Koons (1948) suggests that Frazier Well gravel now at elevations 5660 feet to 7150 feet was derived from the Prescott-Jerome area and was carried into place by north flowing drainage. Because no such drainage system now exists, Koons postulates a drainage reversal possibly associated with the development of Basin-Range structures.

Relationships between location of gravel deposits, source outcrops, and present plateau surface strongly suggest that at the time of deposition of gravels the plateau was relatively low lying and was bounded by mountain ranges having pre-Cambrian rock cores and drained by east and north flowing streams. This is in line with the hypothesis suggested by Davis (1901) and others that drainage was from the west into the plateau province until after Basin-Range faulting.

Figure 5 suggests conditions at the time of deposition of the plateau gravels. From a lofty range (which may represent an ancestor of the Black Hills Range) much gravel was carried outward and spread as a mantle upon the plateau surface. Relief of the plateau is shown to be negligible at this stage. Whether this is an accurate characterization may be determined when additional studies of the plateau gravels are made. In northeastern Arizona in the Chuska Mountains area (Gregory, 1917) there are Tertiary detrital deposits, but the relationship between these sediments and the gravels here under discussion constitutes a problem beyond the scope of this paper.

That the Colorado Plateau area as seen today represents a relatively stable section of the crust which was encircled by zones of mountain building and igneous activity during the Tertiary period has been suggested by Butler (1929) who calls attention to thick sections of Paleozoic sediments adjacent to the plateau on the east, north and west. Zones of igneous activity and associated mineralization also encircle the plateau. Butler considers the possibility that collapse of the trough of sedimentation caused concentric border folding; igneous activity and mineralization followed. Butler admits that conditions in central Arizona, where the mountain belt bounds the plateau, are not so favorable to his hypothesis because within the mountain belt Paleozoic sections are not particularly thick, and therefore the basic reasons for folding is absent. It is true,

however, that igneous activity and mineralization are outstanding in the mountain belt and the further evidence of gravels strewn upon the plateau surface may indicate, as suggested above, that peripheral mountains did exist in this region.

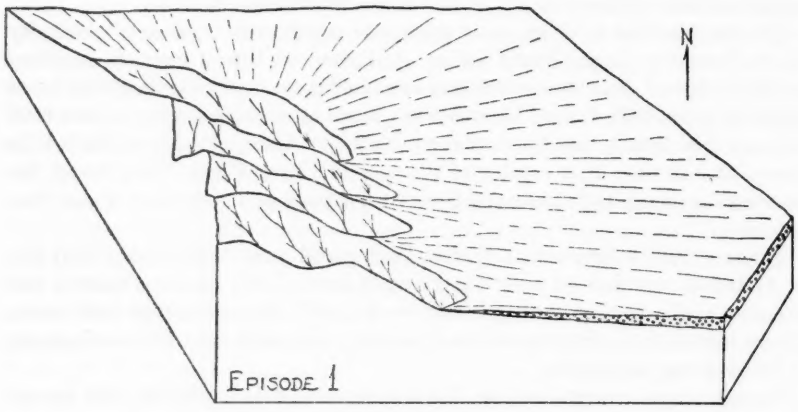


FIG. 5

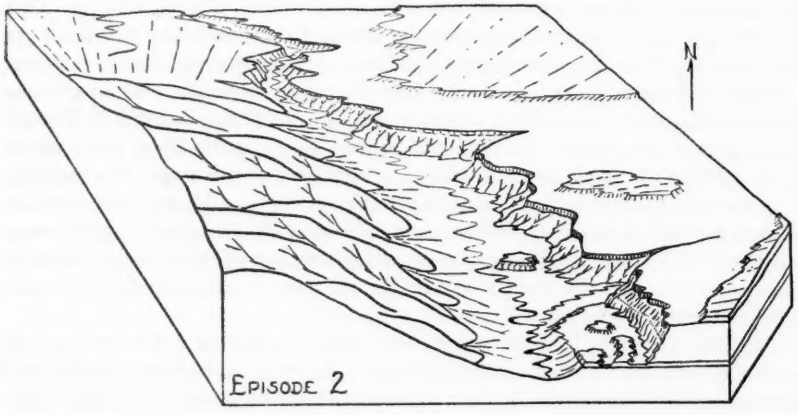


FIG. 6

Further indication that mountain ranges may have existed southwest of, and adjacent to, the plateau area of northern Arizona as far back as the Triassic is found in the Shinarump conglomerate. McKee (1937) described invertebrate fossils found in pebbles taken from this Triassic formation and identified species characteristic of the Kaibab limestone. He states that facies of Kaibab from whence the fossils came is restricted to an area west of a line drawn from Bright

Angel Canyon through Sycamore Canyon south of Flagstaff. Fossils were derived from uplifted outcrops of Kaibab limestone located to the west and south. McKee also calls attention to the fact that the size of the Shinarump pebbles diminishes northeastward suggesting that their source was toward the southwest.

Branson and Mehl (1929) have published paleogeographic maps indicating land areas west and south of the Colorado Plateau in Triassic time.

To state accurately the geologic age of plateau gravel is not possible at the present state of investigation. Price (1948) assigned the gravel to late-Miocene on the basis of evidence elsewhere in the plateau that the development of a Miocene erosion surface was followed by uplift in the latter part of that epoch or in earliest Pliocene time. This uplift, it is thought, would have been responsible for lofty peripheral mountains from which gravels were carried.

Koons' (1948) preliminary investigation has revealed no clue to the age of Frazier Well gravel. He suggests, however, that streams depositing Frazier Well gravels were tributary to the Colorado and that drainage reversal was associated with Basin-Range faulting. These relationships are of little diagnostic value as long as doubt remains concerning the age of the Colorado River and Basin-Range faulting.

Episode Two

Excavation of Ancestral Verde Valley

The first Verde Valley must have been cut after deposition of the plateau gravel otherwise the gravel source would have been cut off. Assuming a late Miocene date for the plateau gravel, the ancestral Verde fits appropriately into the Pliocene, and headward growth of this stream becomes part of the general erosion of the Colorado Plateau. Concerning this erosion Gregory (1947, p. 700) states:

> "... the former low altitude, arid surface was uplifted in late Miocene or very early Pliocene time and carried with it much of the original topography; ... in the process of uplift the surface was fractured and moderately warped; ... in its newly attained lofty position a humid climate made possible the development of fully organized river systems."

Excavation of the ancestral Verde Valley is here called Episode Two. Topography at this time is shown in Fig. 6. The position of Verde Valley suggests that the stream was genetically subsequent and developed headward along some zone of weakness parallel to the trend of Black Hills Range. As the Verde extended its drainage area northwestward it progressively diverted streams flowing out of the highlands onto the plateau surface—streams which had deposited plateau gravel. The northeast valley wall of the Verde would have been composed of horizontal strata of the plateau and during this episode the erosional escarpment known as the Mogollon Rim, or the Verde Breaks, first came into existence.

Field work carried out in preparation of this paper was largely concerned with deciphering the series of events which followed initial cutting of Upper Verde Valley.

Episode Three

Alluviation of Ancestral Verde Valley

The oldest alluvial material now in Upper Verde Valley is a gravel deposit located five miles south of Big Park near the road junction and the crossing with Dry Beaver Creek. The notable feature of these gravels is that in spite of their location across the present valley from the Black Hills Range, they contain high percentages of pre-Cambrian rock types (52% toward top of section measured) and except that they are in the valley, they appear to be identical with gravels described by Price high up on the plateau surface. A section of the Verde Valley gravels nearly 300 feet thick was measured (Plate 3). The gravels overlie an irregular surface developed upon the Supai formation. The presence of this gravel remnant probably results from protection from erosion afforded by a lava cap. The locality is twelve miles from the nearest outcrops from which pre-Cambrian material was derived. Elevation of the gravel surface beneath the lava cap is 4200 feet.

The 300 feet of gravel varies in grade size and bedding characteristics from bottom to top. Where it is in contact with the underlying Supai formation the gravel is coarsest and is composed of rock types locally derived. Higher in the section there are layers of fine sediment and limestone which closely resemble members of Verde formation. The presence of these beds, particularly the limestone, indicates that during deposition of the gravel temporary lakes existed upon the alluvial surface.

Pebbles of pre-Cambrian rock are found most abundantly near the top of the section, indication that the chief source of gravel was then from the west. The lack of cross-bedding in the thick upper member (Plate 3) indicates a sheet wash type of deposition. Wind-faceted and wind-pitted pebbles are abundant in this gravel, similar to conditions which prevail on alluvial plains in the southwest today.

Inasmuch as pebbles of pre-Cambrian rock are found in the upper part of the section at an elevation of 4200 feet, it is assumed that there was a "ramp" leading upward from that elevation to the ancestral Black Hills Range; down this ramp the gravel was transported. Whether the ramp was a pediplane or was produced by alluviation of a deep valley cannot be ascertained. If a pediplane, the 300 feet of gravel might by accident represent the greatest thickness anywhere deposited. If the hypothesis of a filled valley is accepted, the thickness of gravel may have been much greater toward the west. The amount of gravel deposited cannot be ascertained, because there is no way of determining how much gravel lying above elevation 4200 feet was removed by erosion previous to emplacement of the lava cap which now protects it.

Fig. 7 illustrates the episode described above. Near the letter "A" at the front of the block certain conditions actually observed in the field are illustrated. The alluvium is seen to bury steep-sided mesas, buttes, and pinnacles, which were developed during excavation of the Episode Two valley. If the drawing represents conditions which prevailed, it is clear that the gravel highest in the section

would be richest in pre-Cambrian rock pebbles derived from the mountains. In the drawing the filled-valley hypothesis for producing the ramp is adopted. The absence of pre-Cambrian rock type pebbles at the base of the section is thought to mean that the floor of the Episode Two valley at its maximum depth was west of, and at a lower elevation than, the bedrock surface upon which the gravel was laid down. Not until that valley was filled was there a ramp across which the mountain-derived pebbles could be carried.

During this episode, extensive deposits of alluvial material, carried into the valley from the west, pushed the Verde toward the east side of the valley. This may account for a part of the width of the present Upper Verde Valley. The width of the valley has heretofore been an unsolved problem, especially since the idea that it is a graben has been abandoned with failure to discover continuous faults along the Mogollon Rim.

Fig. 7 shows a series of pediments along the plateau front which were developed as alluviation of the valley proceeded. Horse Mesa and the region immediately south of it along the Mogollon Rim is a beautifully preserved remnant of one of these pediments. A mesa one mile west of Sedona is also interpreted as a pediment remnant; its position with respect to Oak Creek suggests that it may have been cut by an ancestor of that stream.

The Oak Creek Canyon fault mentioned by Johnson (1909, p. 139) cuts deep into the plateau margin bounding Upper Verde Valley. The upper portion of Oak Creek flows approximately along the fault line. At Indian Gardens the fault line leaves the valley and continues straight southward, running east of Munds Mountain (Mears, 1948). The fault follows the upper portion of Jacks Canyon and can be traced without difficulty into the north wall of Horse Mesa; but significantly, there is no displacement of the surface of the mesa. It is clear that the last movement along the Oak Creek Canyon fault occurred earlier than cutting of the pediment.

The Horse Mesa pediment problem is related to Episode Five when the lava flow which caps the pediment was emplaced.

Episode Four

Re-excavation of Verde Valley

Episode Four in the chronology of Upper Verde Valley, consisting of excavation of the extensive gravel fill of the previous episode, resulted in the valley which was later to become the site of ancient Lake Verde (Fig. 8). Depth of the valley excavated during this episode cannot be definitely stated, but if evidence of well logs (Jenkins, 1923) is accepted, lake beds extend downward to elevation 2000 feet. If, as assumed above, the gravel fill of Episode Three reached at least 4200 feet elevation, more than 2000 feet of material was removed during the re-excavation. This figure applies to the south-central part of the valley; the thickness downstream may have been greater, that upstream not so great.

Toward the end of Episode Four re-excavation Sycamore Creek, a tributary stream at the north end of Upper Verde Valley, joined the Verde at what is now elevation 3680 feet. The stream in SOB Canyon joined the main stream at some-

what less than 3500 feet. Gravels are preserved at these elevations under lava flows in the two tributary valleys (Plate 6). A large part of the evidence of Episode Four re-excavation of the main valley is similarly dependent upon the present position of flows poured out during Episode Five.

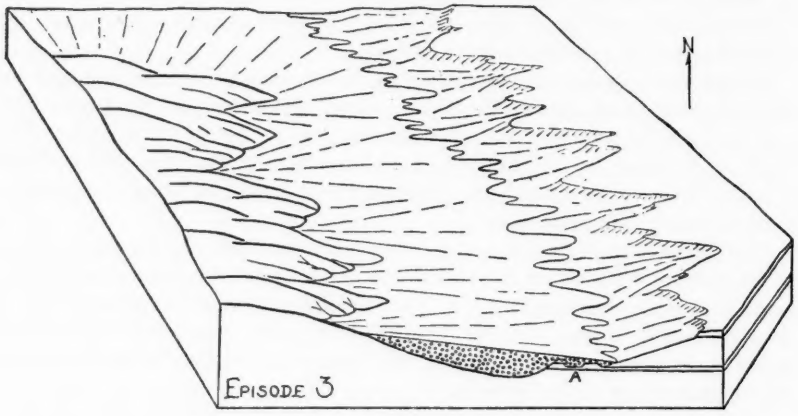


FIG. 7

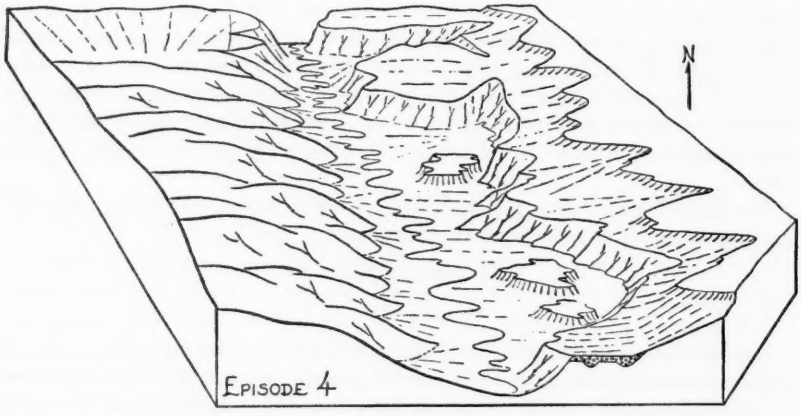


FIG. 8

During Episide Four re-excavation, the Verde River shifted laterally southwestward across the valley, reversing the trend which was characteristic during Episode Three deposition. Perhaps the Black Hills Range had been lowered by erosion and received less rainfall. At the same time tributary streams issuing from the higher plateau block forced the Verde across the valley. Lavas which later flowed off the plateau on to the valley floor may have contributed to the migration.

Episode Five

Igneous Activity

In the fifth episode lavas entered the Verde Valley from several places. Lava flows in Sycamore and SOB Canyons, mentioned above, moved down the two tributary valleys and cut into the wide valley of the Verde. The flows now underlie an area known as Duff Flat (Plate 4). In Fig. 8 these flows are shown.

Sycamore Canyon flow near the junction of Sycamore Creek and the Verde River lies on Paleozoic bedrock. The present elevation of the top of the flow is 3723 feet and the thickness is between 40 and 50 feet. The Verde has trenched the flow in the present cycle and it now forms prominent "palisade" cliffs along the canyon (Plate 5). At several localities there are exposures of the pre-lava mantle which is now a conglomerate and represents cemented alluvium of the Verde deposited prior to emplacement of the lava. This cemented alluvium is clearly a normal deposit of an actively downcutting stream rather than a remnant of the gravel fill deposited during Episode Three of this chronology.

The lava flow which moved down SOB Canyon and into the Verde Valley underlies the Sycamore Canyon flow. In Plate 4 both flows may be seen. There is no evidence of a fossil soil horizon upon the older flow and no other evidence that its upper surface was exposed to weathering and erosion for any long period; therefore it is concluded that the two flows are almost contemporaneous. The SOB Canyon flow had its source high up in Black Hills Range and may be related to the flows which now cap Mingus and Woodchute Mountains. The flow moved down a valley of steep gradient cut in Paleozoic bedrock and containing coarse gravel. In the present cycle the stream in the canyon has cut through lava to expose underlying gravel and bedrock.

Pre-lava gravel (Plate 6) is very distinctive and is found at many localities along the east side of Black Hills Range and also beneath the lava caps which surmount the range. It is pinkish in color due to the presence of sandy components and pebbles derived from Supai and Redwall formations. This gravel is locally derived and is not to be correlated in its entirety with the gravel deposited during Episode Three. Regional relationships of the "pink" conglomerate undoubtedly will be understood more clearly when detailed geologic mapping of the Clarkdale and Mingus Mountain quadrangles is completed by the U. S. Geological Survey.

At the same time lava flows were entering the north end of the re-excavated Verde Valley there occurred extensive igneous activity in the central part of the valley. Approximately opposite the mouth of Oak Creek there was built upon an irregular Paleozoic bedrock surface, at the present elevation of 3500 to 4000 feet, a shield volcano now called House Mountain (Fig. 9). Successive lava flows built up to a thickness of more than 1000 feet and the structure covers at present an area of approximately 60 square miles. Many lava-capped buttes adjacent to U.S. Highway 89A represent erosional remnants of flows which spread northward from the House Mountain center. Similar flows spread southward from the volcano and are described in Episode Six.

The course of Oak Creek crosses the north flank of House Mountain and along the valley there are exposures of the contact between Paleozoic bedrock and lava flows. The contact is irregular, giving evidence that the pre-lava surface was one of considerable relief.

The Horse Mesa region also experienced igneous activity during this episode. From the plateau surface on the east, lava flowed down the pediment surfaces which still remained from Episode Three. The lava flowed far enough to come to rest upon remnant areas of Episode Three gravel fill. This fortunate occurrence accounts in large measure for the preservation of these gravels to the present time.

As stated previously Horse Mesa pediment surface is not broken by the Oak Creek Canyon fault, and of course the lava cap is similarly undisturbed. This is of interest because Johnson (1909, p. 139) observed that lavas in and near Oak Creek Canyon are offset by fault movement. In this observation Robinson (1913) and Mears (1948) concur. If it is assumed that movement occurred at only one time along the whole length of the fault, lavas of Oak Creek Canyon and those which cap Horse Mesa are of two different epochs, with faulting intervening.

Lavas of Oak Creek Canyon which are broken by faulting are said by Robinson (1913) to be related to those of the first general period of volcanic activity in the San Francisco Mountain area. He assigns a late Pliocene date to these flows. Colton (1937) added information concerning the San Francisco Mountain volcanic field and divided the igneous activity into five stages. He follows Robinson in classifying Oak Creek flows as oldest.

Robinson (1913, plate III, p. 20) maps lava flows of the third stage of eruption in the Black Mesa (Morman Mountain) area, 14 miles northeast of Horse Mesa. Evidence already introduced that the Horse Mesa lava cap is younger than the Oak Creek Canyon flows, coupled with the proximity of the Mormon Mountain area to the Horse Mesa pediment, leads to the conclusion that the Horse Mesa flow should be correlated with Stage III lavas.

R. P. Sharp (1942) studying glaciation of San Francisco Mountain found evidence of Iowan-Wisconsin glaciation. From these glaciers there was spread outwash which passes beneath lavas of Stage III, thus dating them as late-Pleistocene. The possibility exists that Horse Mesa lavas should be correlated with Stage II lavas of middle-Pleistocene age, but Robinson (1913) indicates no flows of Stage II in the Mormon Mountain area, and there is no other evidence in favor or this correlation or against it.

Additional evidence of the recent date of lavas associated with Episode Five is furnished by relationships in the Sycamore Canyon area. Lavas flowed down a valley already cut to a depth of several hundred feet through the entire thickness of the Stage I basalts and deep into underlying Paleozoics (Price 1948). According to the sequence of events here suggested, the time available for this cutting would have been the time from the late Pliocene to the middle or late Pleistocene. On the other hand, Sycamore Creek has cut vertically approximately 100 feet since Stage III flow was emplaced. This represents cutting accomplished since late Pleistocene. It should be borne in mind, however, that during part of

this time Sycamore Creek could not erode its lower course because its base level rose with the rising waters of Verde Lake.

It is significant to note that Childs (1948) found Stage III lavas in the basin

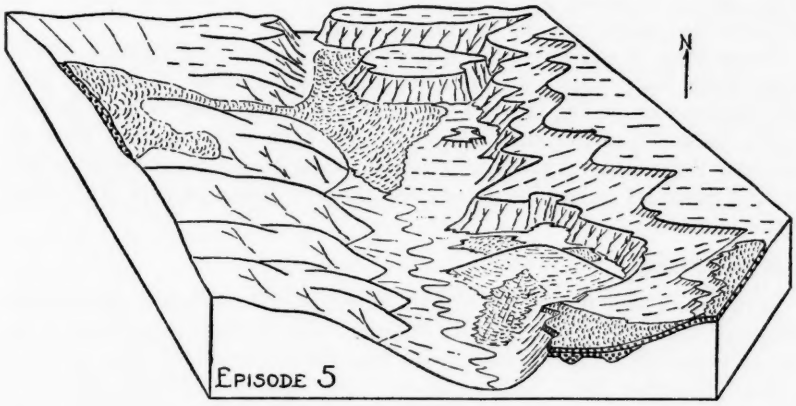


FIG. 9

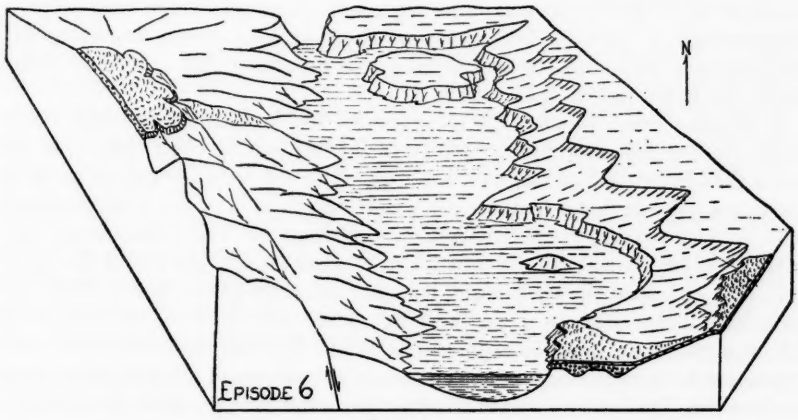


FIG. 10

of the Little Colorado River occupying stream channels nearly modern in their character. This is similar to the Sycamore Canyon situation.

Episode Six

Verde Lake Sedimentation

Where the Verde River made its way between the southward continuation of the Black Hills Range, the Mogollon Rim, and the northward continuation of the

Mazatzal Mountains, there occurred enough volcanic activity to form a dam and cause impounding of the river to bring into existence Verde Lake (Fig. 10). Jenkins (1923) writes of the "basalt dam"; however where rocks constitute the dam outcrop, beginning ten miles south of Camp Verde on the road to Strawberry, one is impressed by the enormous quantity of pyroclastic rocks—tuffs and breccias—which underlie the rugged terrain.

The problem of correlating this igneous activity with other volcanic activity of the Verde Valley area is a critical one. It is clear, of course, that lavas, tuffs, and breccias constituting the dam are just slightly older than Verde Lake sediments. Inasmuch as this same age relationship holds with regard to lavas described in Episode Five, i.e. House Mountain, Horse Mesa, etc., which are judged to be of Stage III or late Pleistocene age, the lava dam is perhaps of the same period of activity.

Interbedded Lavas

Lavas which were poured out to form House Mountain were at least in part contemporaneous with the lake sedimentation. This has been established by discovery along Dry Beaver Creek of two lava flows interbedded with lake sediments. The higher flow is visible from the main highway to Montezuma Castle National Monument and the lower flow outcrops in the bed of Dry Beaver Creek upstream one half mile from the point where the first flow is seen. At this locality the lower flow is 23 feet thick and it is overlain by 20 feet of angular conglomerate characteristic of lake bed-lava contacts wherever they occur. Including the conglomerate, there are 100 feet of lake beds separating the lower and upper flows. The upper flow is 34 feet thick.

A question arises whether the lavas flowed out beneath the water of Verde Lake. Neither flow shows pillow structure. At one point a filled channel in the lower flow indicates that the flow was exposed to sub-aerial erosion after being emplaced. Also in this area there are conglomerate beds in the lake sediments with cobbles ranging up to twenty inches in diameter. The conglomerates are interpreted as alluvial deposits spread by streams beyond the end of the upper lava flow and upon the temporarily emerged lacustrine plain. One of these conglomerate layers outcrops along the highway one mile north of the turn-off to Montezuma Castle National Monument (Plate 7). The elevation of the conglomerate beds compared to the elevation of the margin of the lava flows bears out the relationship here suggested. After the emplacement of the flow and the deposition of gravel beyond its margin, lake waters rose once more, inundating the region, and deposition of lake sediments continued. Several large rounded boulders of basalt are embedded in the limestones which compose the wall of Montezuma Well. These boulders are thought to have had an origin similar to the conglomerate beds.

Both interbedded lava flows can be traced northward toward House Mountain and although the dissection in the present stage is not deep enough to enable one to observe the flow actually joining the shield volcano, it seems entirely likely that this is true.

Highest Lake Level

Sedimentation in Verde Lake continued until the basin was filled with conglomerates, sandstones, siltstones and limestones to the present elevation of approximately 4300 feet. This maximum is indicated by the consistent elevation of the highest outcrops of lake sediments at that elevation today, on the flank of House Mountain, in the area west of Coffee Creek Ranger Station, on the flank of Black Mountain, and in the lake bed area north of the smelter in Clarkdale. In no instance were shoreline erosional features observed such as wave-cut cliffs or wave-erosion platforms. The hypothesis is advanced that Verde Lake was not a deep body of water but was always a great playa lake with sedimentation occurring almost as rapidly as the lake level rose. This condition would preclude the formation of large waves which would attack the shores to produce wave-erosion landforms.

Jenkins (1923) points to the presence of salt deposits found in Camp Verde vicinity as evidence that the lake possessed no outlet. This indicates that the climate of central Arizona when Verde Lake was in existence was not greatly different than today, and that loss of water by evaporation was largely responsible for the lake being shallow and not overflowing its outlet. This suggestion is not consistent with statements made elsewhere in this paper that deep weathering of basalt fragments in basal, lake bed breccia indicates a more humid climate.

Fossils

Diligent search was made throughout the period of two field seasons for fossils in the Verde formation. The nearest approach to a find was made in a limestone member near the top of the section of rocks north of the smelter at Clarkdale. Here were found some small gastropods belonging to the large family Helicidae. Only external molds were found and positive identification of genus and species was not made.*

The most unusual fossils ever collected from the Verde formation were sets of mammal tracks in limestone obtained by Nininger (1942). No detailed study of these fossils has been published. Certain of the Nininger fossils were purchased by the American Museum of Natural History in New York City and Simpson (1949) has made the following statement concerning them:

"No attempt has been made to identify the tracks in any very precise way beyond generally noting that they include tracks of cats, camels, bears, and so forth. Although it might con-

*Since this paper was first sent to the printer and through the kindness of Prof. Walter Bucher of Columbia University, Dr. Teng-Chien Yen of the U.S. National Museum has identified five genera of mollusks from the upper limestone member of the Clarkdale smelter section. The following is quoted from a letter from Dr. Yen. "The collection contains the following genera of mollusks and the state of preservation of the available specimens does not permit any of the identifications to species: Sphaerium sp., Lymnaea sp., Physa sp., Gyraulus sp., ? Pupilla sp. The above assemblage of forms, with the exception of the Pupilla-like one, seems to indicate well its enclosing deposit to be a normal shallow water facies. Species of these genera generally require a habitat area covered by a rich growth of submerged plants in a body of water possibly not over ten feet in depth."

ceivably be possible in a few cases to run the identification down somewhat closer, I think that it would be virtually impossible to correlate these tracks with any particular genera or, still more, species. It is therefore exceedingly questionable whether the tracks could be used for dating with any really useful precision. It might, for example, be possible to say that the tracks were Pleistocene rather than Pliocene if they happened to include *Bison* tracks, which apparently is not the case. As far as we have gone with the tracks about all that can be said is that they appear to be late Tertiary or Quaternary."

The scarcity of fossils in the lake sediments may be cited as additional evidence that Verde Lake was shallow and saline throughout its existence; its waters may not have been palatable and large numbers of animals were not attracted to it.

Faults

In an early section of this paper Black Hills Range was described as a fault-block mountain bounded on the northeast by normal faults, the most impressive of these being the Main or Verde fault with a throw in the Jerome area of 1700 feet. An important part of the chronology should be to determine the date, or relative date at least, of these faults. As discussed by Lindgren there is confusion as to whether faulting is earlier than lake beds (Lindgren, 1926, p. 56) or cuts lake beds (Lindgren, 1926, p. 12). On the geologic map accompanying the study by Lindgren, one parallel fault is shown abutting or cutting lake beds at a point 2–3 miles north of the Jerome-Clarkdale road. This area was examined carefully and no such fault could be located although at approximately the place where the fault is shown, there is a normal depositional contact between Verde formation and underlying lavas.

North and south of the Jerome-Clarkdale highway, a noticeable topographic element is a series of spurs leading down from summit portions of Black Hills Range. Crests of these spurs are composed of a great thickness (up to 100 feet) of very coarse and angular gravel which overlies the irregular lava surface. Color of the gravels is determined by a preponderance of lava as well as greenstone fragments and it was referred to in the field as "gray" gravel. Near the bottoms of steep-walled gulches cut into the mountain side there is frequently exposed another angular gravel which underlies lavas and overlies the Paleozoic sequence from which it was obviously derived. Its color is characteristically pink and this was assigned as a field name to differentiate it from the post-lava or gray gravel.

Fig. 11 is a composite cross-section which shows relationships of pre-Cambrian rocks, Paleozoic sediments, lavas, lake sediments of Verde formation, and gray and pink gravels, as they exist in the Clarkdale-Jerome area. The Paleozoic section beneath the lava cap of Woodchute Mountain is as complete as shown only toward the north end of Black Hills Range; further south the Paleozoic cap was removed by pre-lava erosion and lavas lie directly upon pre-Cambrian. The fault splinter in the figure is based upon observations made in Mescal Gulch; there are exposures of Paleozoic bed rock, of pre-lava pink gravel, of lava, and post-lava gray gravel. The region between the faults and the mesa of lake sediments is correctly shown as far as topography is concerned but no precise information is available concerning underlying Paleozoic structure which of necessity is over-simplified in the section.

SOB Canyon cuts through the mesa underlain by the Verde formation, exposing the irregular lake bed-lava contact and the angular basal breccia (Plate 8). Also along this canyon the dissection is deep enough to expose pink gravel lying upon Paleozoic, Supai formation (Plate 6), and the whole overlain by lava and lake sediments. At the right end of the cross-section, the Verde River is shown in its box canyon cut into two lava flows which underlie the Duff Flat region (Plate 4). In the cross-section an attempt has been made to show the peneplane developed upon pre-Cambrian rocks at approximately correct elevations above sea level. For example, the peneplane southwest of Jerome is at 6000 feet, just northeast of the Verde Fault it is at 4230 feet (Lindgren, 1926, p. 11), and beneath the Verde River near Clarkdale (approximately at northeast end of section), the peneplane was encountered in drilling at elevation 1200 feet (Findlay, 1918).

At no place in the field was a fault observed breaking lake sediments; and at no place were lake beds observed overlapping a fault. Both faults shown in Fig. 11, of course, occurred too high up on the mountain flank to have cut lake sediments

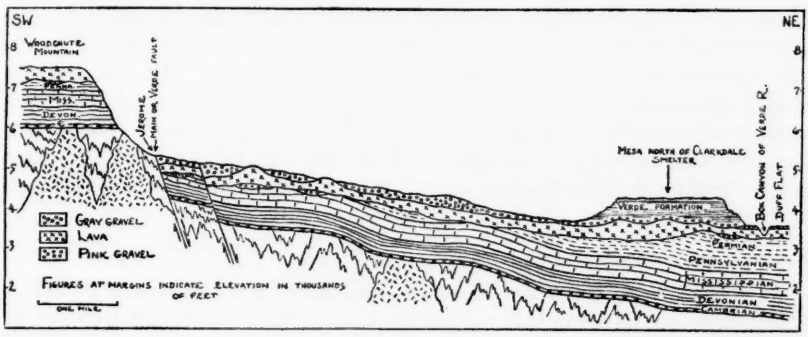


FIG. 11

assuming, as suggested elsewhere, that lake sedimentation extended only to elevation 4300 feet. Age relationships between faults and lake sediments must therefore be determined by studying the relationship of each to some common formation, in this case either lavas or gray gravels. There can be no doubt that lavas are broken by the Verde Fault and because lake sediments overlie lavas, both the most recent faulting and lake sediments are younger than lavas.

Gray Gravel

In the field gray gravel may be seen butting against the fault planes; this relationship is shown in Fig. 11. The lower part of the gray gravel is interpreted as a residual mantle which formed upon the lava surface previous to faulting; the upper layers of gravel on the down-thrown side of the fault represent a talus apron shed from the fault scarp both during and after it was formed. In other words, part of the gravel seen in contact with the fault plane was dropped into position by faulting, and part of it was simply piled against the fault plane after being mass-wasted and in other ways eroded from the up-thrown block. The

gray gravel represents a talus and alluvial apron deposited in front of the fault scarp. Angularity and lithology of the gravel bears this out. Gray gravel in the Clarkdale-Jerome area is composed of a mixture of about equal quantities of basalt and greenstone and other pre-Cambrian crystalline rock types. The pre-Cambrian type of rock was derived from the scarp face exposed by faulting, and the basalt from flows beneath the gravel or from lava lying upon the crest of the up-thrown block. Paleozoic rock types are present in the gravel but not in large quantity. All such pebbles would have had to be derived from the Paleozoic cap on the up-thrown block.

A clue as to whether Verde Lake had formed when the deposition of gray gravel was going on may be obtained by restoring the original slope of the alluvial pediment. When this is done, the slope appears to have been graded to a level below that finally achieved by the lake; but it is doubted that the base level at the time was as low as the Verde River *before* the lake began to rise. This analysis suggests that there was present an interfingering relationship between gray gravels and lake sediments. In the area north of the Clarkdale-Jerome highway where interfingering would be expected to occur, erosion has unfortunately been vigorous and outcrops at the proper level are missing. There are present in this area outcrops of very angular, limestone-cemented breccia (Plate 2), but the breccia immediately overlies lava and may be no different than basal breccia seen elsewhere in the valley. In spite of the lack of outcrop, however, it is thought that the interfingering relationship between gray gravel and lake sediments is most reasonable, thus requiring that faulting and lake sedimentation were contemporaneous.

Railroad Bend Structure

At a point along the Verde River one mile below the junction of Sycamore Creek there occurs along the railroad an outcrop of rock types and structures pictured in Plate 9. This locality is so unique that special treatment is warranted. Jenkins (1923, p. 70) described this structure and drew a fault separating the Paleozoic Supai formation from basalt and lake sediments. Interpretation here presented is at variance with that of Jenkins.

In the diagram a lava flow, which is the one emerging from Sycamore Canyon (Plate 5) is shown resting against the flank of a monoclinal fold striking N 20° E with dips as high as 45° E and developed in the Supai formation. No evidence of a fault between lava and Supai was observed, but there was evidence of baking and other alteration of the sandstone and siltstone adjacent to the contact. Atop the lava there rests a gravel bed averaging 18 feet in thickness largely composed of Supai pebbles with diameters up to 10 inches carried down on to the lava surface from the slope of the monocline. The gravel is overlain by limestone layers deposited by the rising and encroaching Verde Lake; these beds therefore overlap the conglomerate. Above the first limestone layer there occurs a series of sandstone and limestone beds each overlapping the one below. As may be observed in the photograph, lake beds are dipping as much as 15°. Much of this dip is interpreted as original or as the result of compaction of sediments. The greater

compaction occurred where the wedge of sediments lapping against the flank of the monocline was thickest, less compaction occurred at the inner, thin edge of the wedge. Difference in amount of compaction also accounts for lessening of dip higher in the lake sediment section which is seen in the photograph. The presence of numerous solifluction structures in the lake beds adjacent to the steeply-dipping monoclinal flank is evidence in favor of compaction and movement of the lake beds during consolidation.

In summary, the rock relationships near the Sycamore-Verde junction do not involve post-Verde formation faulting or folding or even post-lava movements. There is revealed, however, a sample of strong flexures of much earlier date which characterize the Paleozoic sequence at the north end of Black Hills Range.

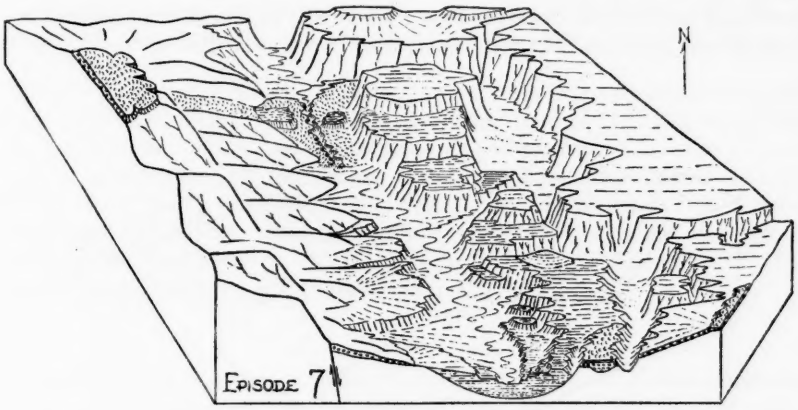


FIG. 12

Episode Seven

Post-Verde Lake Erosion

The seventh and last episode in the chronological development of Upper Verde Valley involves extensive erosion in the present cycle (Fig. 12). This cycle could have been inaugurated in two different ways. The layer of lake sediments may have finally been built high enough to decrease the basin capacity sufficiently to allow the limited amount of water to rise to the level of the lowest point along the crest of the lava-tuff dam. Once water flowed across the top of the dam, downcutting of the outlet would have commenced, the lake would have been drained and lake sediments would be eroded. The second possibility is that a stream tributary to a drainage area south of the dam worked headward and captured the lake basin. In this way the lake was drained and the Verde River led southward along the general route it had followed previously.

Once drainage was established across the crest of the dam, vertical downcutting may have been rapid, and the Verde soon cut a valley into lake sediments. In-

spection of the lower valley of Oak Creek reveals a pattern of well-developed intrenched meanders. It is noted that the meandering habit is not too evident where the elevation of Oak Creek is higher than 4300 feet. If, as suggested above, the lake sediments built up to that level and not higher, that elevation would be the location of a former break in the longitudinal profile of Oak Creek and would mark the spot where the creek emerged from plateau rocks to flow across the gently sloping lacustrine plain. On this surface it developed the meanders which were intrenched when Oak Creek lowered its channel to keep abreast of the rapidly downcutting Verde.

Study of landforms present in Upper Verde Valley today reveals evidence of at least two sub-stages in Episode Seven dissection. Along the front of Black Hills Range are some excellent high level pediments. Plate 10 shows a splendidly developed pediment southwest of Camp Verde. The pediment surface slopes two degrees and truncates lake sediments which have local dips up to 10°. As is

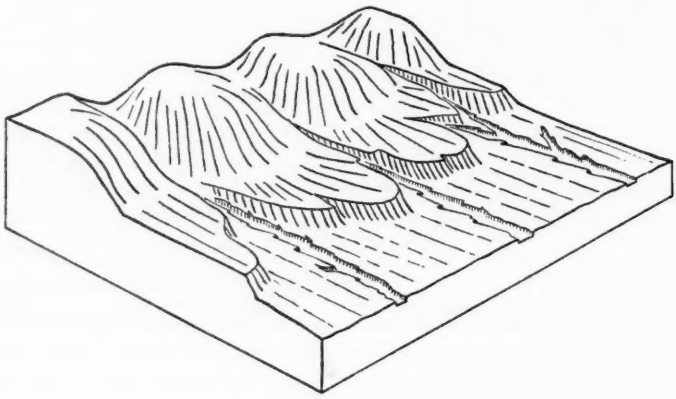


FIG. 13

characteristic, the pediment is mantled with a veneer of gravel. An excellent cross-section of the pediment is visible in the field because it is undergoing dissection. This is clearly seen in Plate 11, which is a view looking down on the pediment surface.

Another high level pediment is located four miles south of Cottonwood. The road serving Goddard Ranch crosses the pediment surface just north of that ranch. The smaller contour interval of the Mingus Mountain quadrangle is responsible for causing this pediment to stand out on the map. The slope of the Goddard Ranch pediment is three degrees and lake sediments here are horizontal. In the case of both pediments, the surface cuts into gray gravel spurs.

The high level pediments may be remnants of a series developed during a period when the Verde was graded to a local base level, perhaps a resistant lava layer in Verde Lake dam area.

When a new period of downcutting of the Verde began, tributary streams commenced dissection of pediments and a second surface at the foot of Black Hills

Range was developed at an elevation approximately 150 feet lower than the high level pediment surfaces (Plate 12). The general slope of the lower surface is the same as that of the high level pediments. This surface is well developed from Clemenceau (Cottonwood) Airport northward to Clarkdale. It is gravel strewn and it is worth noting that there is no appreciable difference in the appearance of the gravel mantle of the high and low surfaces as far as degree of weathering is concerned, although one level is obviously older than the other.

As is generally true throughout the southwest today, there is evidence in Upper Verde Valley of a very recent cycle of downcutting frequently referred to as the "arroyo" cycle. Streams flowing from Black Hills Range, characteristically dry except in times of heavy rain, have incised themselves from 10 to 30 feet into the low-level pediment surface. The arroyos constitute a third element in the assemblage of erosional landforms along Black Hills Range mountain front. Fig. 13 illustrates diagramatically the relationship of the three elements in the piedmont topography.

In the process of eroding its present valley, the Verde has produced numerous rock terraces overlain by gravel, sometimes to depths of 15 to 20 feet. These terraces are particularly well developed at Cottonwood and Clarkdale with excellent exposures along U. S. Highway 89A, and at Camp Verde where the town itself is built upon a terrace surface. Terrace gravels, well rounded by virtue of being transported long distances, contrast considerably with the gravel upon pediment surfaces which is very angular, having been transported but a few thousand yards from the mountain range.

SUMMARY

The excavation of Upper Verde Valley and development of present landforms in the valley occurred during Pliocene and Pleistocene epochs. The first valley was undoubtedly cut when uplift at the end of Miocene inaugurated the "canyon cutting" cycle recognized by Davis, Johnson, etc., in the Grand Canyon district to the north. In this respect Upper Verde Valley resembles other valleys of the Colorado Plateau including the Grand Canyon. The valley was then filled with gravel and pediments were developed as at Horse Mesa on the east side. Pedimentation followed outpouring of Stage I lavas on the plateau and faulting in Oak Creek Canyon.

The valley was re-excavated and tributary canyons were cut almost to their present depth. Outpouring of lava occurred on the valley floor, flowed down tributary canyons, and the lava-tuff dam blocking the Verde River was emplaced. This lava activity is correlated with Stage III lavas in the San Francisco Mountain area which are younger than Iowan-Wisconsin glaciation. This correlation is a critical one and unfortunately is not well enough established to be relied upon. The alternative exists that the lavas on the surface of the Horse Mesa pediment may be correlated with Stage II flows which would place them in the middle Pleistocene. This correlation is attractive from the standpoint of allowing more time for subsequent events, but Robinson indicates no Stage II flows in the Mormon Mountain area from whence came the Horse Mesa flows.

During filling of the Verde Lake basin by sediments, some outpouring of lava occurred. Faulting along the northeast flank of Black Hills Range also took place. Debris shed from the fault scarps is thought to have been intercalated with lake sediments.

The present cycle of erosion has resulted in partial removal of the lake sediments. Two pediment levels in the present valley are interpreted as the result of local base level control rather than as evidence of regional warping.

Robinson's (1913) conclusion that all igneous activity associated with the San Francisco Mountain area falls in late Pliocene or within the Pleistocene epoch has been widely accepted. That the Verde formation is younger than, or the same age as, the associated volcanics has been firmly established. This relationship coupled with the complex history of Upper Verde Valley worked out above makes clear the fact that the main conclusion of this paper involves an appraisal of the tremendous magnitude of depositional, erosional, and tectonic activity which has occurred just prior to, within, and since the Pleistocene epoch in Upper Verde Valley.

WORKS TO WHICH REFERENCE IS MADE

ALLEN, AGNES M. (1937) *The sequence of human occupancy in the Middle Rio Verde Valley, Arizona*, unpublished Doctoral dissertation, Clark University, Worcester, Massachusetts.

ANDERSON, C. A. (1947) personal communication.

BLAKE, W. P. (1890) *Thenardite, mirabilite, glauberite, halite and associates of the Verde Valley, Arizona*, Am. Jour. Sci., vol. 39.

BRANSON, E. B. AND MEHL, M. J. (1929) *Triassic amphibians from the Rocky Mountain region*, Univ. Missouri Studies, vol. 4, no. 2, p. 21.

BUTLER, B. S. (1929) *Relation of the ore deposits of the southern Rocky Mountain region to the Colorado Plateau*, Colorado Sci. Soc. Proc., vol. 12, p. 23–36.

CHILDS, O. E. (1948) *Geomorphology of the valley of the Little Colorado River, Arizona*, Geol. Soc. Am., Bull., vol. 59, p. 353–388.

COLTON, H. S. (1937) *The basaltic cinder cones and lava flows of the San Francisco Mountain volcanic field, Arizona*, Bull. no. 10, Museum of N. Arizona, Flagstaff, Arizona.

DAVIS, W. M. (1901) *An excursion to the Grand Canyon of the Colorado*, Harvard Univ., Mus. Comp. Zool., Bull., vol. 38, p. 107–201.

FINDLAY, J. R. (1918) *The Jerome district of Arizona*, Eng. and Min. Jour., vol. 106, Sept. 28 and Oct. 5.

GREGORY, H. E. (1917) *Geology of the Navajo Country*, U. S. Geol. Survey, Prof. Paper 98.

GREGORY, H. E. (1947) *Colorado Drainage Basin*, Am. Jour. Sci., vol. 245, p. 694–705.

JENKINS, O. P. (1923) *Verde river lake beds near Clarkdale, Arizona*, Am. Jour. Sci., vol. 5, p. 65–81.

JOHNSON, DOUGLAS W. (1909) *A geological excursion in the Grand Canon district*, Proc. Boston Soc. Nat. Hist., vol. 34, no. 6, p. 135–161.

KOONS, E. D. (1948) *High level gravels of western Grand Canyon*, Science, no. 2784, p. 475–476.

LINDGREN, W. (1926) *Ore deposits of the Jerome and Bradshaw Mountains quadrangles, Arizona*, U. S. Geol. Survey, Bull. 782.

LONGWELL, C. R. (1946) *How old is the Colorado River?* Am. Jour. Sci., vol. 244, p. 817–835.

MCKEE, E. D. (1937) *Triassic pebbles in northern Arizona containing invertebrate fossils*, Am. Jour. Sci., vol. 33, p. 260–263.

MEARS, BRAINERD (1948) personal communication.

NININGER, H. H. (1941) *Hunting pre-historic lion tracks in Arizona*, Plateau, vol. 14, no. 2, Museum of N. Arizona, Flagstaff.

PRICE, W. E. (1948) *The rim rocks of Sycamore Canyon*, unpublished thesis, Graduate College, University of Arizona.

RANSOME, F. L. (1903) *Geology of the Globe copper district, Arizona*, U. S. Geol. Survey, Prof. Paper 12.

REBER, LOUIS E. (1921) *Geology and ore deposits of Jerome district*, Trans. A.I.M.E., vol. 66.

ROBINSON, H. H. (1913) *The San Francisco volcanic field*, U. S. Geol. Survey, Prof. Paper 76.

RUSSEL, I. C. (1885) *Geological history of Lake Lahontan*, U. S. Geol. Survey, Monograph XI.

SIMPSON, G. G. (1949) personal communication, Feb. 14.

SHARP, ROBERT P. (1942) *Multiple Pleistocene glaciation on the San Francisco Mountain, Arizona*, Jour. of Geol., vol. 50, p. 481-503.

STRAHLER, A. N. (1949) personal communication.

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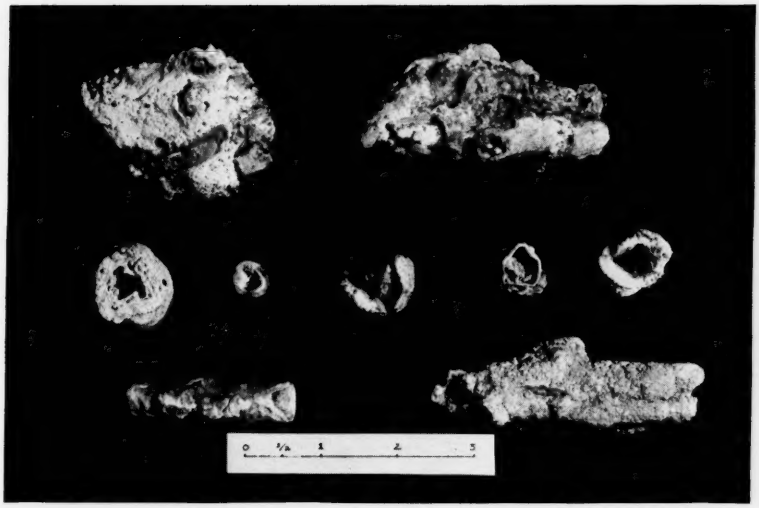

PLATE 1. Stem incrustations from the Verde formation

PLATE 2. Characteristic view of angular, basal breccia in Verde formation. Foot is on contact; note filling of joints in lava below contact.

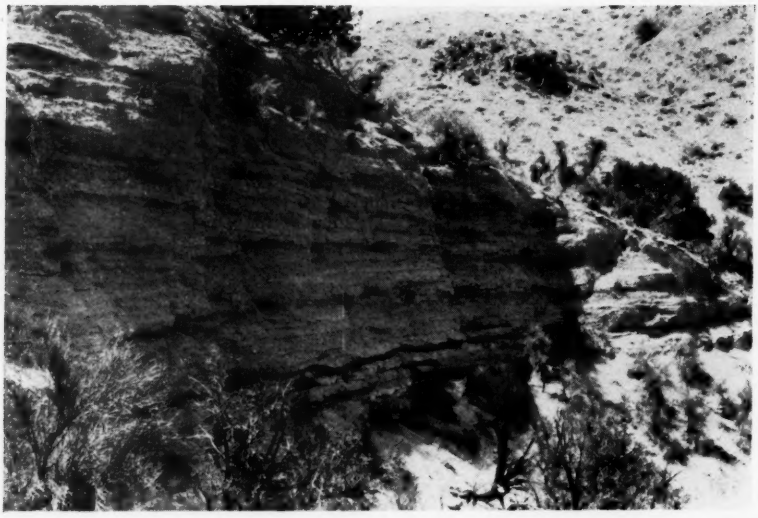

PLATE 3. Remnant of Episode Three gravel fill. Note lava cap in upper right background. Thickness of gravel section here shown is 55 feet.

PLATE 4. Duff Flat lava flows as seen along box canyon of Verde River. Thickness of top flow, 30 feet. Lower flow issued from SOB Canyon; top flow from Sycamore Canyon. See also Plates 5, 9.

PLATE 5. Sycamore Canyon lava flow at junction of Sycamore Creek and Verde River. Paleozoic strata compose hill rising above flow and also may be seen underlying flow in center of view.

PLATE 6. Pre-lava "pink" gravel outcrop in SOB Canyon. Overlying lava is apparent in upper left corner of view.

PLATE 7. Conglomerate interbedded with lake sediments. Largest boulders are twenty inches across.

PLATE 8. Irregular contact of lake sediments and lava as seen northwest of Clarkdale.

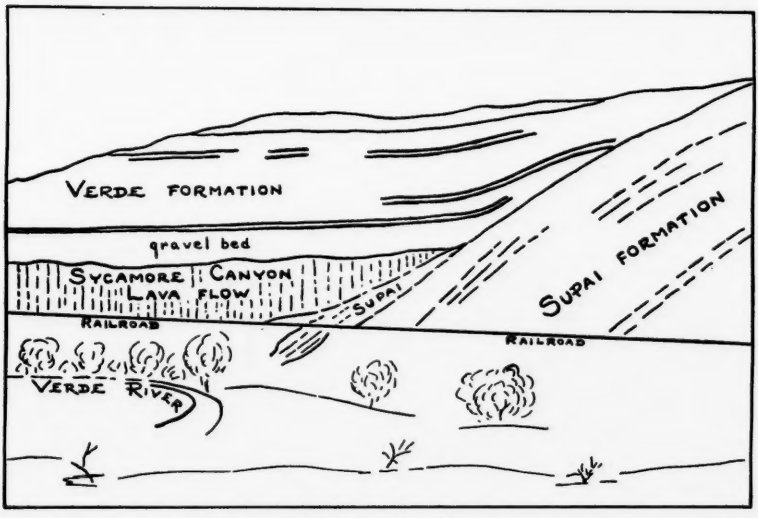

PLATE 9. Railroad Bend Structure

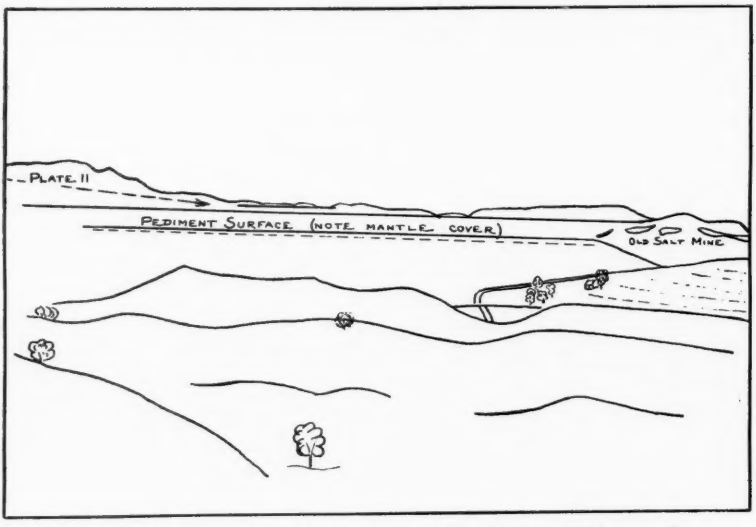

PLATE 10. Pediments southwest of Camp Verde, view looking north

PLATE 11. Looking down on Camp Verde pediment, Salt Mine in distance. See Plate 10

PLATE 12. Low level pediment (brush covered surface, middle of view) north of Cottonwood Airport.

The Denison Scientific Association

Report of the Secretary

Under the direction of the President, Dr. A. W. Lindsey, the Association presented the usual program of meetings during the academic year 1948–9, though more than half of the semi-monthly sessions were closed meetings for the discussion of problems of interest to the Association. Lectures were presented in open meetings according to the following schedule.

October 26, 1948

The Yellowstone National Park

A lecture illustrated by numerous colored slides, by Dr. H. V. Truman, Assistant Professor of Biological Sciences

November 9, 1948

The Propagation of Ultrasonics in Single Crystals

A lecture by a Denison Alumnus, Dr. William J. Price, of the Battelle Memorial Institute, Columbus, Ohio

November 23, 1948

The Mounds of Licking County, Ohio

A well illustrated lecture by Richard H. Howe, Assistant Professor of Physics

March 22, 1949

Salt Water, Submarines and Sound

A lecture based on personal experiences, by Samuel C. Wheeler, Instructor in Physics

The final meeting of the year, on May 10, 1949, followed a dinner for members, at the Colwell Dining Hall. There were presented the reports of officers and some informal discussions of the policies, plans and program of the Association; and the following results of the election of officers for the year 1949–50 were announced.

President,	Dr. Conrad E. Ronneberg
Vice-president,	Dr. H. V. Truman
Secretary-treasurer,	Miss Dorothy Carpenter
Secretary and Editor, *Journal of the Scientific Laboratories*,	Dr. W. A. Everhart
Librarian,	Dr. L. E. Smith

Report by
W. A. Everhart, *Secretary.*

New Species of Bryozoans from the Pennsylvanian of Texas; Raymond C. Moore. 17 pp., 1 plate.
Articles 4–5, pp. 165–200, August, 1930.....$1.00
Visual Localization in the Horizontal Plane; Winford L. Sharp. 9 pp.
Petroleum Products for Internal Combustion Engines; Milton Finley. 26 pp., 3 figs.
Articles 6–7, pp. 201–299, December, 1930.....$1.00
The Actinoceroids of East-Central North America; Aug. F. Foerste and Curt Teichert. 96 pp., 33 plates.
The Presence of Nybyoceras in South Manchuria; Riuji Endo. 3 pp., 1 plate.

VOLUME 26

Article 1, pp. 1–142; April, 1931.....$1.50
The Hesperioidea of North America; A. W. Lindsey, E. L. Bell and R. C. Williams, Jr. 142 pp., 33 plates.
Article 2, pp. 143–250; December, 1931.....$1.50
The Older Appalachians of the South; Frank J. Wright. 108 pp., 38 plates.

VOLUME 27

Article 1, pp. 1–46; June, 1932.....$1.50
The Geomorphic Development of Central Ohio (Part I); Henry S. Sharp. 46 pp., 1 fig., 6 plates.
Article 2, pp. 47–136; December, 1932.....$1.50
Black River and Other Cephalopods from Minnesota, Wisconsin, Michigan, and Ontario (Part I); Aug. F. Foerste. 90 pp., 31 plates.

VOLUME 28

Articles 1–3, pp. 1–154; April, 1933.....$1.50
Black River and Other Cephalopods from Minnesota, Wisconsin, Michigan, and Ontario (Part II); Aug. F. Foerste. 146 pp.; for plates *cf.* This Journal, Vol. 27, Art. 2 (December, 1932).
A Study of the Change in Mass of the Anode of the Aluminum-Lead Cell; Charles E. Welling. 5 pp.
Balancing Chemical Equations—The Contribution of Otis Coe Johnson (1880); W. C. Ebaugh. 4 pp., 1 plate.
Article 4, pp. 155–248; October, 1933.....$1.00
The Ordos Desert of Inner Mongolia; George B. Cressey. 94 pp., 32 figs., 1 plate.

VOLUME 29

Article 1, pp. 1–105, April, 1934.....$1.25
The Newer Appalachians of the South (Part I); Frank J. Wright. 105 pp., 28 plates, 3 figs.
Article 2, pp. 107–193, August, 1934.....$1.25
Silurian Cyrtoconic Cephalopods from Ohio, Ontario, and Other Areas; Aug. F. Foerste. 86 pp., 14 plates.
Articles 3–4, pp. 195–238, December, 1934.....$1.00
Evidence of Ice Action in the Teays Valley, West Virginia; Julian J. Petty. 10 pp., 4 figs.
The Earlier History of the BULLETIN OF THE SCIENTIFIC LABORATORIES OF DENISON UNIVERSITY; Aug. F. Foerste. 23 pp.

VOLUME 30

Articles 1–2, pp. 1–118, April, 1935.....$1.00
Big Horn and Related Cephalopods; Aug. F. Foerste. 96 pp., 22 plates.
New Light Sources for Photographic Purposes; W. E. Forsythe. 22 pp., 7 figs.
Articles 3–4, pp. 119–230, August, 1935.....$1.00
Correlation of Silurian Formations in Southwestern Ohio, Southeastern Indiana, Kentucky and Western Tennessee; Aug. F. Foerste. 87 pp.
A Study of the Phenomenon of Wetting Films; C. W. Chamberlain and Kenneth Lyle Warren. 25 pp., 4 plates, 1 fig.
Articles 5–6, pp. 231–303, December, 1935.....$1.00
The Cephalopods of the Maquoketa Shale of Iowa; Aug. F. Foerste. 27 pp., 11 plates.
New Genera of Ozarkian and Canadian Cephalopods E. O. Ulrich and Aug. F. Foerste. 32 pp., 1 plate.

VOLUME 31

Articles 1–2, pp. 1–92, April, 1936.....$1.00
Hierosaurus colei; a new aquatic Dinosaur from the Niobrara Cretaceous of Kansas; M. G. Mehl. 20 pp., 3 plates.
Silurian Cephalopods of the Port Daniel Area on Gaspé Peninsula, in Eastern Canada; Aug. F. Foerste. 72 pp., 23 plates.
Article 3, pp. 93–142, August, 1936.....$1.00
The Newer Appalachians of the South (Part II): South of the New River; Frank J. Wright. 50 pp., 6 figs., 32 plates.
Articles 4–6, pp. 143–259, December, 1936.....$1.00
A Study of the Vestigial Air Bladder in the Darter (*Catonotis flabellaris rafinesque*); George David Morgan. 16 pp., 10 plates.
e Must Shape our New World (Commencement Address); Arthur Holly Compton. 11 pp.
Later History of the JOURNAL OF THE SCIENTIFIC LABORATORIES OF DENISON UNIVERSITY; Kirtley F. Mather. 25 pp.
Report of the Permanent Secretary of the DENISON SCIENTIFIC ASSOCIATION. 52 pp.

VOLUME 32

Articles 1–2, pp. 1–131, April, 1937.....$1.00
History of *Theta* Chapter of Ohio, Phi Beta Kappa (1911–1936); Willis A. Chamberlin. 69 pp., 2 figs.
The Tungsten Filament Incandescent Lamp; W. E. Forsythe and E. Q. Adams. 72 pp., 10 figs.
Articles 3–7, pp. 133–207, August, 1937.....$1.00
Science and the College (Commemoration Address); Carey Croneis. 12 pp.
Our Endowment (Commemoration Address); C. Judson Herrick. 9 pp.
Science—Man's Liberator (Commemoration Address); William E. Wickenden. 10 pp.
The Application of Physics to Modern Hydrographic Surveying; (Commemoration Address); Herbert Grove Dorsey. 22 pp., 10 plates.
An Annoted Check-list of Birds Recorded at Granville, Licking County, Ohio; Ward M. Klepfer and William J. Taylor. 21 pp., 1 plate.
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